

Excitation of Alfvén Waves and Pulsar Radio Emission

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ABSTRACT

We analyze mechanisms of the excitation of Alfvén wave in pulsar magnetospheres as a possible source of pulsar radio emission generation. We find that Cherenkov excitation of obliquely propagating Alfvén waves is inefficient, while excitation at the anomalous cyclotron resonance by the particles from the primary beam and from the tail of the bulk distribution function may have a considerable growth rate. The cyclotron instability on Alfvén waves occurs in the kinetic regime still not very closed to the star: $r \geq 50 R_{NS}$. We also discuss various mechanisms of conversion of Alfvén waves into escaping radiation. Unfortunately, no decisive conclusion about the effectiveness of such conversion can be made.

1. Introduction

Interpretations of various observational data tend to place the location of radio emission generation at a distance $r \approx 10 - 100 R_{NS}$ (e.g., Phillips 1992), though there plenty of claims to the contrary (Kijak et al. 1999, Smirnova et al. 1996, Gwinn et al. 1997). As was pointed out by Kunzl et al. (1998) and Melrose & Gedalin (1999), even with the most conservative estimates of the efficiency of plasma production in the polar caps, the plasma frequency at those heights is much larger than the observed frequency. This argues against radio emission mechanisms that generate Langmuir waves with a frequency near the local plasma frequency (Asseo et al. 1990, Whitheter 1997). von Hoensbroech et al. (1998) argued that this implies a strong underdense production of particles, but the theoretical foundations of such an assumption are weak. Alternatively, Melrose & Gedalin (1999) argued that in order to restrict emission to small altitudes the emission should be generated at frequencies much smaller than the plasma frequency, preferably on Alfvén waves. They considered excitation of oblique Alfvén waves by the Cherenkov resonance with plasma and found that it mostly produces waves with $\omega \sim \omega_p$ and thus cannot resolve the problem. Though we agree with their conclusion that Cherenkov excitation of Alfvén waves is insignificant in the pulsar magnetosphere, we disagree on the reasons why. First, we do not agree with the conclusion of Melrose & Gedalin (1999) that Cherenkov resonance of the beam particles with the Alfvén waves occurs outside the light cylinder for the conventional beam energies. It actually occurs for radii $r \leq 50 R_{NS}$ (see section 2). Secondly, they assumed that Cherenkov excitation of Alfvén waves occurs in a kinetic regime, while it was shown in Lyutikov (1999) that Cherenkov excitation of Alfvén waves occurs in a hydrodynamic regime.

On the other hand, some authors postulated excitation of the Alfvén mode and, using the fact that Alfvén is guided along the curved magnetic field, were able to explain some observational data like dependence of the mean profile on the frequency (e.g. Barnard & Arons 1986, McKinnon 1994, Gallant 1998, Gwinn et al. 1999). The above arguments stimulated us to reconsider the possibility of excitation of Alfvén waves at the low altitudes in the magnetosphere, *including* the excitation of waves at anomalous cyclotron resonance.

A major theoretical problem of the theories that produce radio emission on Alfvén waves is that Alfvén waves cannot escape from the plasma and have to be converted into escaping radiation (preferably X mode). In section 5 we review various possibilities of Alfvén waves conversion into escaping modes.

2. Waves and resonances

The open field lines of the pulsar magnetosphere are populated by the dense one-dimensional flow of electron-positron pair plasma penetrated by highly energetic primary beam with the density equal to the Goldreich-Julian density $n_{GJ} = \mathbf{\Omega} \cdot \mathbf{B} / (2\pi e c)$, Lorentz factor $\gamma_b \approx 10^6$ (Arons 1983, Daugherty & Harding 1996). The density of the pair plasma is $n \approx \lambda_M n_{GJ} = 10^3 - 10^5 n_{GJ}$, where λ_M is the multiplicity factor which gives the number of pairs produced by each primary particle; its Lorentz factor is $\gamma_p \approx \gamma_b / \lambda_M = 10 - 10^3$. The distribution function of the bulk plasma also has a high energy tail up to the Lorentz factor $\gamma_t \approx 10^5$.

Though the pulsar plasma is thought to be relativistically hot, we restrict ourselves to cold plasma case which simplifies consideration considerably. Except for the Landau damping of the waves with slow phase velocity, thermal effects has only marginal importance for the wave-particles interaction and growth rates of instabilities (Lyutikov 1999a). In what follows we consider wave excitation in the plasma frame and then use the transformation rules of the Lorentz factors and frequencies from the plasma frame to pulsar frame: $\gamma' = 2\gamma_p\gamma$, $\omega'_p = \sqrt{\gamma_p}\omega_p$, $\omega'_B = \omega_B$, where primes denote quantities in the pulsar frame and γ_p is the Lorentz factor of the relative motion of the plasma frame to the pulsar frame.

In the strongly magnetized pair plasma, in the small frequency limit $\omega \ll \omega_p$, there are two modes - transverse extraordinary (X) mode, with the electric vector perpendicular to the $\mathbf{k} \cdot \mathbf{B}$ plane, and quasitransverse Alfvén wave with the electric vector in the $\mathbf{k} \cdot \mathbf{B}$ plane. In the plasma frame the dispersion relations of the extraordinary and Alfvén modes are (e.g. Lyutikov et al. 1999a).

$$\omega_A = kc \cos \theta \left(1 - \frac{\omega_p^2}{\omega_B^2} - \frac{k^2 c^2 \sin^2 \theta}{4 \omega_p^2} \right), \quad \text{for } \omega \ll \omega_p \quad (1)$$

$$\omega_X = kc \left(1 - \frac{\omega_p^2}{\omega_B^2} \right) \quad (2)$$

The plasma normal modes can be excited due to interaction with particles at the Cherenkov

$$\omega - k_{\parallel} v_{\parallel} = 0 \quad (3)$$

and anomalous cyclotron resonances

$$\omega - k_{\parallel} v_{\parallel} + \omega_B / \gamma_{res} = 0 \quad (4)$$

where ω is a frequency of the wave, k_{\parallel} and v_{\parallel} are projections of the wave vector and velocity along the direction of the magnetic field, ω_B is a (nonrelativistic) cyclotron frequency and γ_{res} is a Lorentz factor of the particles. Also note plus sign in front of the cyclotron term in Eq. (4). Two regimes of excitation are possible: kinetic and hydrodynamic.¹

The X mode can not be excited by the Cherenkov-type interaction since it has $\mathbf{E} \perp \mathbf{B}, \mathbf{v}$. At radii larger than $\approx 50 R_{NS}$ (see Eq. 5) the phase velocity of the X mode becomes smaller than the velocity of the primary beam with $\gamma_b \approx 10^6$, so it can in principle be excited by cyclotron resonance, but near the surface of the neutron star the growth rate of the cyclotron excitation of the X mode is extremely small and the frequencies do not correspond to observed ones (Lyutikov 1999a). The cyclotron excitation of X mode

¹ In a hydrodynamic type instability all the particles of the beam resonate with one normal wave in the plasma, while in a kinetic regime only small fraction of the beam particles resonates with a given wave.

may occur in the outer region of pulsar magnetosphere and is considered as a viable mechanism of pulsar radio emission generation (Kazbegi et al. 1989, Machabeli & Usov 1989, Lyutikov et al. 1999b). Thus, we conclude that near the surface the X mode cannot be excited and in what follows we concentrate on the possible excitation of the Alfvén mode.

3. Cherenkov excitation of the Alfvén mode

The Cherenkov excitation of Alfvén waves has been considered in detail by Lyutikov (1999a). On a microphysical scale it is similar to the Cherenkov excitation of the Langmuir waves - the motion of the resonant particle is coupled to the component of the electric field of the wave along the magnetic field (and the velocity of the particle). It is possible only for oblique propagation since Alfvén waves which have a component of electric field parallel to the external magnetic field $e_z \approx \sin \theta$.

Using resonance condition (3) and the low frequency asymptotics of Alfvén waves (1) we infer that that the possibility of the Cherenkov excitation of the Alfvén waves by the particles from the primary beam depends on the parameter

$$\mu = \frac{2\gamma_b \omega_p}{\omega_B} = 2^{3/2} \gamma_b \sqrt{\frac{\lambda \Omega}{\omega_B}} = 2^{3/2} \sqrt{\frac{\lambda \Omega}{\omega_B}} \frac{\gamma'_b}{\gamma_p^{3/2}} = 5 \times 10^{-3} \left(\frac{r}{R_{NS}} \right)^{3/2} = \begin{cases} < 1, & \text{if } \left(\frac{r}{R_{NS}} \right) \leq 50 \\ > 1, & \text{if } \left(\frac{r}{R_{NS}} \right) \geq 50 \end{cases} \quad (5)$$

Alfvén waves can be excited by Cherenkov resonance only for $\mu < 1$, when the phase velocity of the fast particles may become equal to the phase velocity of obliquely propagating Alfvén waves (see Figs. 6 and 6). When $\mu > 1$ the particles move faster than the beam and, due to the specific dispersion of Alfvén waves, cannot resonate with them. In the outer parts of magnetosphere ($r \geq 50 R_{NS}$) parameter μ becomes much larger than unity $\mu \gg 1$ so Alfvén waves cannot be excited by Cherenkov interaction.

The resonant condition for the Cherenkov excitation of Alfvén waves (Eq. 3) may be solved for $k_\perp = k \sin \theta$:

$$k_\perp = \omega_p \sqrt{\frac{1}{2\gamma_b^2} - \frac{\omega_p^2}{\omega_B^2}} \quad (6)$$

As expected, excitation is limited to $\frac{\omega_p^2}{\omega_B^2} < \frac{1}{2\gamma_b^2}$, e.i. for $r \leq 50 R_{NS}$.

The growth rate for the Cherenkov excitation of Alfvén waves (which occurs in the hydrodynamic regime) has been calculated in Lyutikov (1999) (see also Godfrey et al. 1975):

$$\Delta = \frac{\sqrt{3} \omega_p^{\frac{1}{3}} \omega_{GJ}^{\frac{2}{3}} \cot \theta}{2^{\frac{7}{6}} \gamma_b^{\frac{8}{3}}} \quad (7)$$

where $\omega_{GJ}^2 = 4\pi e^2 n_{GJ}/m$ is the plasma frequency associated with the Goldreich-Julian density. It is very similar to the growth of the Cherenkov excitation of Langmuir waves. This result is expected since the microphysics of the Cherenkov excitation of Langmuir and Alfvén waves is the same - coupling of the parallel (to the magnetic field) motion of particles to the parallel component of the electric field of the wave. Consequently, the growth rate given by Eq. (7) for the Alfvén wave excitation suffers from the same problem as Langmuir wave excitation: it is strongly suppressed by large Lorentz factor of the primary beam. We thus conclude that Cherenkov excitation of the Alfvén waves is ineffective.

4. Cyclotron excitation of the Alfvén mode

The other possibility of excitation of Alfvén waves is by the anomalous cyclotron resonance (Tsytovich & Kaplan 1972, Hardee & Rose 1978, Lyutikov 1999a). On a microphysical scale, during an emission at the anomalous cyclotron resonance, a particle undergoes a transition *up* in Landau levels coupling transverse velocity to the electric field of the wave (Ginzburg & Eidman 1959).

In case of low frequency ($\omega_A \ll \omega_p$) waves, the the resonance condition for the cyclotron excitation of Alfvén reads

$$k_{res} c \cos \theta \left(\frac{1}{2\gamma_b^2} - \frac{\omega_p^2}{\omega_B^2} - \frac{k^2 c^2 \sin^2 \theta}{4\omega_p^2} \right) + \omega_B / \gamma_b = 0, \quad k_{res} c \ll \omega_p \quad (8)$$

If the third term is much larger than the first two (this happens for the angles of propagation larger than some critical angles $\frac{\omega_p}{\gamma_b \omega}$ and $\frac{\gamma_b \omega_p^4}{\omega_B^4}$) the resonance occurs at

$$k_{res} c = \left(\frac{4\omega_p^2 \omega_B}{\gamma_b \cos \theta \sin^2 \theta} \right)^{1/3} \approx \frac{\omega_p}{\mu^{1/3}} \left(\frac{1}{\cos \theta \sin^2 \theta} \right)^{1/3} \quad (9)$$

The condition $\omega_{res} \ll \omega_p$, which guarantees that Alfvén waves are not damped by the Cherenkov interaction with the bulk plasma particles, requires $\mu \gg \frac{1}{\cos \theta \sin^2 \theta}$, or equivalently, $r \geq 50R_{NS}$. This is a serious restriction: Alfvén waves cannot be excited at lower altitudes since then the cyclotron resonance occurs in the region where Alfvén waves are strongly damped due to Cherenkov resonance with the bulk particles (Arons & Barnard 1986).

Cyclotron excitation of Alfvén waves occurs in kinetic regime (Lyutikov 1999a). The growth rate is

$$\Gamma = \frac{\pi}{4} \frac{\omega_b^2}{\omega_{res} \Delta\gamma} \quad (10)$$

where $\Delta\gamma$ is the scatter in Lorentz factors of the resonant particles and the resonant frequency ω_{res} follows from Eq. (9). Formally, growth rate for the cyclotron instability on Alfvén waves (Eq (10)) is the same as the growth rate for the the cyclotron instability on the high frequency transverse waves (Lyutikov et al. 1999b, Kazbegi et al. 1989), which occurs in the outer parts of the pulsar magnetosphere. The important difference is that the cyclotron instability on Alfvén waves can occur at lower altitudes, where the density of the resonant particles is higher. ²

Numerically, for the emission generated at $r \approx 50R_{NS}$ and a quite narrow primary beam ($\Delta\gamma \approx 10^2$ - see Lyutikov et al. 1999a), we have

$$\Gamma \approx 10^5 \text{sec}^{-1} \quad (11)$$

Thus, we conclude that the growth rate of the cyclotron instability on the Alfvén waves may be considerable enough to account for the high brightness pulsar radio emission.

5. Wave conversion

There are two fundamental problem with Alfvén waves - they cannot escape from plasma and they are damped on the Cherenkov resonance with plasma particles when their frequency becomes comparable

²In the case of Alfvén waves we use the dispersive correction $k_{\perp}^2 c^2 \sin^2 \theta / \omega_p^2$ instead of ω_p^2 / ω_B^2 .

to ω_p . As Alfvén waves propagate into decreasing plasma density, their frequency will eventually become comparable to the plasma frequency (Barnard & Arons 1986). Before that, Alfvén waves have to be converted into escaping modes. The conversion should take place at such radii that the local plasma frequency, transformed into the pulsar frame, is still larger than the observed frequencies: $r \leq 500R_{NS}$.

There are two generic types of conversion - linear and nonlinear. Linear conversion occurs in the regions where WKB approximation for wave propagation is not satisfied (e.g., Zheleznyakov 1996). Nonlinear conversion is due to the wave-wave or wave-particles interaction. In order to escape absorption at the Cherenkov resonance the Alfvén waves should be converted into either superluminous ordinary waves or into X modes that does not have a component of the electric field along the external magnetic field.

5.1. Linear conversion

Linear conversion of waves occurs when dispersion curves of two modes approach each other closely on the $\omega - k$ diagram. Effective conversion occurs when the distance between two dispersion curves becomes comparable to the "width" of the dispersion curve. Several processes can contribute to the broadening of the dispersion curve. First, the inhomogeneity of the medium induces a width $\frac{\delta\omega}{\omega} \approx \frac{1}{kL}$ where L is a typical inhomogeneity scale. Inhomogeneities can be due both to large scale (of the order of the light cylinder radius) density fluctuations, excited by temporal and spatial modulations of the flow, and due to the small scale plasma turbulence. Linear conversion of Alfvén waves into X mode is impossible because of their different polarizations. Linear conversion of Alfvén waves into O mode can occur only when the frequency of the Alfvén waves approaches plasma frequency, i.e. exactly at the moment when Alfvén waves become strongly damped at the Cherenkov resonance with the bulk plasma. The effectiveness of the conversion then depends on the not very well known details of the bulk plasma distribution function (e.g., distributions with considerable high energy tail will tend to damp the waves stronger), so no decisive argument about the effectiveness of such conversion can be made.

Secondly, the wave turbulence results in effective collisions (with frequency ν_c) of Alfvén waves with each other; in this case the induced width is $\delta\omega \approx \nu_c$.³ For a given turbulent energy density W_{tot} the typical wave-wave collision frequency (based on a three wave interaction) can be estimated as

$$\nu_c \approx \left(\frac{e}{mc}\right)^2 \frac{W_{tot}}{\omega_p} \quad (12)$$

Effective conversion occurs when this frequency is of the order of the minimum difference between the dispersion curves. In the case of strong turbulence the collision frequency becomes comparable to the frequency of the waves near the conversion point: $\nu \approx \omega_p$. In that case the required wave energy density is approximately equal to the energy in plasma. Assuming that the energy density of plasma is of the order of the thermal energy, we find

$$W_{tot} = \left(\frac{\omega_p mc}{e}\right)^2 \approx nmc^2 \quad (13)$$

In addition, in the pulsar plasma the energy in the secondary plasma is approximately equal to the energy in the beam. Then, the energy density given by Eq. (13) is of the order of the beam energy. The amount of energy lost by a beam due to the wave excitation depends on the complicated physics of the instability

³Terminology here may be a bit confusing: the frequency of collisions, of course, depends on the total energy density of turbulence.

saturation mechanisms, but we can reasonably expect that to be $\sim 1 - 10\%$. In this case the collisional frequency $\nu_c \sim 0.01 - 0.1\omega_p$ and the collisional conversion of Alfvén waves into O mode can be marginally effective.

Another mechanism of linear wave transformation is related to the presence of velocity shear in the flow (Arons & Smith 1979, Mohajan et al. 1997, Chagelishvili et al. 1997). We can reasonably expect that the flow of pair plasma has some shear associated with the plasma generation in the polar gap. Given a strong shear Langmuir waves become coupled to the escaping O modes. Whether the shear expected in the polar outflow can provide enough coupling remains uncertain.

5.2. Nonlinear conversion

5.2.1. Wave - wave interaction

Consider a merger of two Alfvén waves into escaping X or O mode. For the three wave processes to take place, the participating waves should satisfy resonance conditions (conservation of energy and momentum) and more subtle conditions on the polarization determined by the matrix elements of the third order nonlinear current (Melrose 1978 Eqs. (10.105) and (10.125)). From the energy and momentum conservation it is easy to see that only oppositely propagating Alfvén waves can merge into X or O mode.

In calculating the matrix element of the three-wave interaction two simplifications are possible in the case of strongly magnetized electron-positron plasma. First, nonlinear current terms which are proportional to an odd power of the sign of the charge will cancel out. Secondly, we can make an expansion in powers $1/\omega_B$ and keep the lowest order. Under these assumption the matrix element becomes

$$V \approx -\frac{ie}{mc} \frac{\omega_p}{\omega_B} \quad (14)$$

Given the matrix element (14) we can find the the probability of emission in the random phase approximation (which assumes that radiation is broadband) (Melrose 1978)

$$u \approx V^2 \omega_p = \frac{e^2}{m^2 c^2} \frac{\omega_p^3}{\omega_B^2} \quad (15)$$

Then, again assuming that the energy density of plasma is of the order of the thermal energy, the characteristic nonlinear decay time is

$$\Gamma \approx \frac{\omega_p^3}{\omega_B^2} = 2^{3/2} \Omega \sqrt{\frac{\lambda_M^3 \Omega}{\omega_B}} \approx 2 \times 10^{-2} \left(\frac{r}{R_{NS}} \right)^{3/2} \quad (16)$$

(compare with Mikhailovskii 1980). So that at the distance $r \approx 50 - 100 R_{NS}$ the nonlinear conversion of Alfvén waves is only marginally possible. The nonlinear conversion of Alfvén waves at lower altitudes is impossible because of the small growth rate.

Thus, we come to a conclusion that though in principle the Alfvén waves can be converted into escaping modes by nonlinear selfinteraction, the conversion must occur at comparatively large radii $r \approx 50 - 100 R_{NS}$. There is another serious problem with nonlinear conversion - it requires a presence of strong backward propagating waves. Presence of such backward propagating waves is not obvious in the pulsar magnetosphere. They should either be excited by a backward propagating fast particles, whose

origin cannot be simply justified, or be a result of a scattering of the initial forwards propagating waves. The Thompson scattering is strongly suppressed in the magnetized plasma and is probably ineffective, but induced scattering (see below) may provide such backward propagating waves.

5.2.2. Induced scattering

Induced scattering of longitudinal waves in pulsar magnetosphere have been considered by Machabeli (1983) and Lyubarsky & Petrova (1996). They showed that it may be an effective process of transferring energy from the Alfvén branch to the O mode. There are several problems with this mechanism. First, the effective induced scattering of Alfvén waves on plasma particles in a superstrong magnetic field occurs in the same region where waves become strongly damped, the question which process is more effective (scattering or damping) again strongly depends on the unknown details of the plasma distribution function. Secondly, if scattering is effective, the induced scattering transfers energy to smallest wave vectors of the O mode (Langmuir condensate). Propagation and escape of the O mode has not been properly investigated, but since the O mode with initially small wave vector has a very small index of refraction ($n \sim 0$) it will be strongly refracted (by the angle $\approx \pi$) as it converts into a vacuum mode with ($n \sim 1$). This strong refraction would then contradict the observed narrow pulsar profiles.

Summarizing this section, we conclude that at this point we cannot make a decisive statement whether linear or nonlinear conversion of Alfvén wave into escaping modes is effective.

6. Conclusion

The results of this work confirm the conclusion of Lyutikov (1999a) that in the pulsar magnetosphere the electromagnetic cyclotron instabilities are the most likely candidates for the pulsar radio emission generation. These instabilities develop on the X and O modes (in the outer regions of the pulsar magnetosphere) and on the Alfvén mode (possibly in the lower, $r \sim 50 - 100R_{NS}$, regions). Cyclotron instabilities on the X and O modes have smaller (than on the Alfvén waves) growth rate, but generate waves that can directly escape from the plasma. The growth rates of the cyclotron instability on Alfvén waves can be very large, but the complications of the wave conversion and absorption in the outflowing plasma, which depend on the unconstrained details of the plasma distribution function, may put the model based on the Alfvén wave excitation at disadvantage.

Both excitation and the nonlinear conversion of Alfvén waves is possible only for $r \geq 50 - 100R_{NS}$. This is a comparatively large altitudes. If we suppose that the opening angle of the magnetic field lines controls the width of the pulsar emission beam (e.g, Rankin 1992), then the value of the opening angle would imply emission right near the surface $r \sim R_{NS}$. If taken at a face value, this interpretation would exclude the Alfvén waves as a source of observed radio emission.

The comparatively large radii of emission, $r \geq 50 - 100R_{NS}$ and larger, may not be that unacceptable from the observational point of view as well (Lyutikov 1999b). Such effects as "wide beam" geometry (Manchester 1995), emission bridge between some widely separated pulses, extra peaks in Crab at high frequencies maybe naturally explained by large altitudes of emission. The results of this work stress one again the difficulties of wave excitation at very small altitudes: Alfvén waves, as well as ordinary and extraordinary modes, cannot be excited beam instabilities or converted nonlinearly into escaping modes

at low altitudes. On the other hand, both excitation and conversion should occur at larger $r \geq 50R_{NS}$ altitudes which remain our preferred regions for the generation of pulsar radio emission.

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FIGURE CAPTIONS

Fig. 1(a). Resonances on the Alfvén mode for $\mu < 1$.

Fig. 1(b). Resonances on the Alfvén mode for $\mu > 1$.



